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Analog of the Gunn effect in heterostructure with two tunnel-coupled quantum well

P. I. Biryulin[†], A. A. Gorbatsevich[†] and Yu. V. Kopaev[‡]

[†] Moscow State Institute of Electronic Technology,
103498, K-498, MIET, Moscow, Russia

[‡] P. N. Lebedev Physical Institute, Russian Academy of Science,
117924, Leninsky prospect, 53, Moscow, Russia

Abstract. Electron transport in heterostructure with two tunnel-coupled quantum well has been numerically investigated under condition of strong non-one-dimensionality of electric field in the structure. It is shown for the first time an ability of the effect in such heterostructures, which is similar to the Gunn effect in bulk semiconductor. The effect is conditioned by the electron tunneling transition between quantum wells with different mobility and is characterized by formation of the strong field domain and the negative differential conductivity region on current-voltage characteristic.

Introduction

Heterostructures with tunnel-coupled quantum wells (HS with TC QW) are a convenient object for investigation of quantum effects in macroscopic system which can be simply registered from changing conductivity of the system. Such structures can be also interesting for the fast electronics because the conductivity changing of HS with TC QW occurs at the electron tunneling transition on short distance. In [1–6] some devices and conductivity models of HS with TC QW were suggested and numerical calculations were executed in the external electric and magnetic field. These results have limited applicability for the calculations of real HS because of their one-dimensionality. 2D or 3D numerical calculations of HS with TC QW have not been done and this fact has conditioned the setting of the task. Since HS with TC QW have macroscopic size and have equivalent characteristics in the plane of QWs it permits to apply 2D calculations.

1. Studied heterostructure

Figure 1 shows physical structure of studied HS. Sheet electron concentration in QW1 is stabilized by donors in the lower barrier. The bottom of QW2 shifts with respect to that of QW1 as the gate is biased. The doping level is selected so that only two first subbands are filled. The mobility μ_{QW2} has been varied in the range 100–1000 cm²/(Vs) at calculations. This mobility is conditioned by scattering on roughness of heterointerface and it is proportional to six degree of the QW width [7]. The mobility in the QW1 is supposed to be equal to electron mobility in 200 Å GaAs QW at 77 K. All calculations are executed for this temperature. If the gate voltage differs from the value corresponding to anticrossing of the first and second quantum levels, the wave functions of the different subbands are localized each in their own QW and the conductivity is implemented mainly by carriers in the QW1. At $V_{gs} \sim -0.7$ V the anticrossing of the first and second subbands takes place and the wave function of each state is situated into both QWs simultaneously.

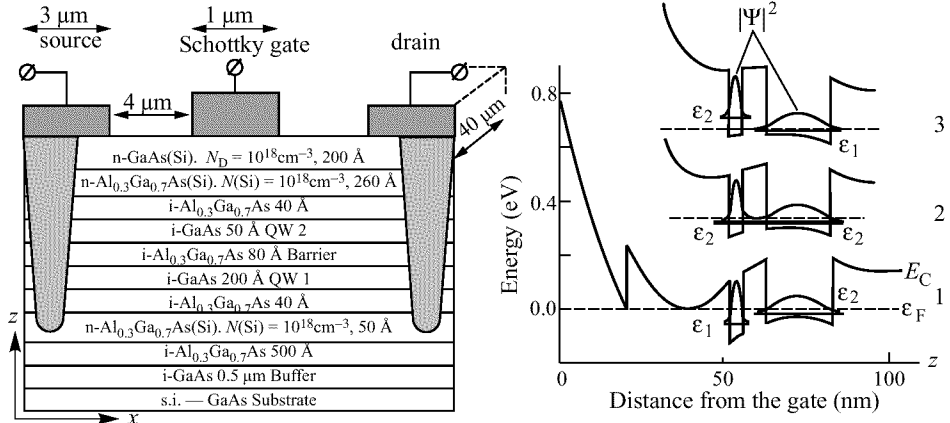


Fig. 1. Structure, topology of contacts and band diagram under the gate at different gate bias, $V_{ds} = 0$ V; (1) 0 V, (2) -0.7 V, (3) -0.9 V.

As consequence, the electrons from both subbands in both QWs scatter on roughness in the QW2. The total mobility and conductivity of the TC QW are decreased.

2. Conductivity model and calculation method

The tunnel connection between QWs can be strong diminished by scattering of the 2D momentum. At character mobility in QWs $10^3 - 10^4$ cm²/(Vs) the broadening of the states in QWs is $\hbar/\tau \sim 10 - 1$ meV. This value is comparable with intervalley tunnel matrix element T in TC QW. $T \sim 0.5 - 5$ meV for the GaAs/Al_{0.3}Ga_{0.7}As system at barrier thickness 50–100 Å. The expression for lateral conductivity of two tunnel-coupled quantum wells taking into account momentum scattering was obtained in [5] with effective mobility:

$$\mu_{eff} = 2\mu \frac{1 + \alpha^2 4\mu^2 (\Delta\varepsilon^2 + 4T^2)}{(1 - \mu_s^2) + \alpha^2 4\mu^2 (\Delta\varepsilon^2 (1 - \mu_s^2) + 4T^2)}. \quad (1)$$

Here μ_1 and μ_2 are mobilities in the separately taken QW1 and QW2 without interaction; $1/\mu = 1/\mu_1 + 1/\mu_2$, $\mu_s = (\mu_1 - \mu_2)/(\mu_1 + \mu_2)$, $\alpha = m^*/e\hbar$, $n = n_1 + n_2$ is the total concentration in both QWs, $\Delta\varepsilon$ energy difference between 1st and 2nd subbands in the absence of tunneling, it is controlled by external field and equals zero at anticrossing. Because of the potential along QWs changes weakly on electron wavelength we solve numerically 1D Schrödinger equation in different TC QW cross-sections along the structure for finding $\Delta\varepsilon$ and T . In the whole HS the 2D Poisson equation and discontinuity equation for electron current is solved numerically. The expression (1) is used as mobility model into TC QW. Diffusion coefficient is determined from Einstein relation. In the whole heterostructure except TC QW, we use mobility model for fonon and impurity scattering. The iteration procedure is used for solving Schrödinger equation consistently with DDM equations.

3. Calculations results

The calculated concentration and mobility in the TC QW, lateral current in the whole HS are presented in Fig. 2. Because of strong broadening of the levels the strongest mobility

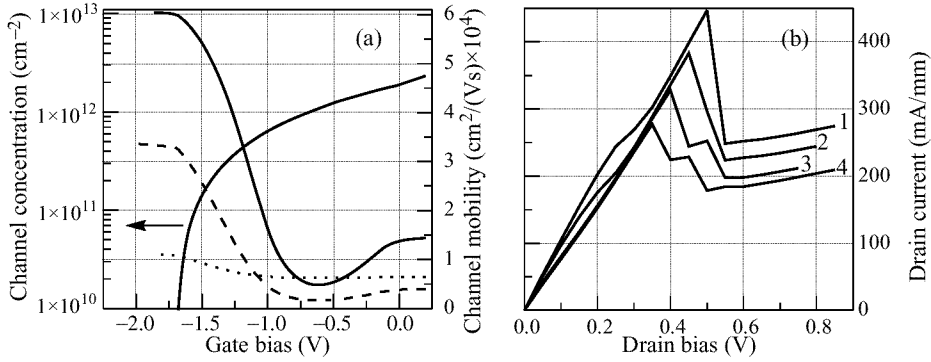


Fig. 2. (a) Dependence of mobility and concentration in TC QW on the gate bias and initial mobility in QW2. Solid line $\mu_{QW2} = 700 \text{ cm}^2/(\text{Vs})$, dashed line $500 \text{ cm}^2/(\text{Vs})$, dotted line $100 \text{ cm}^2/(\text{Vs})$. $\mu_{QW1} = 7 \cdot 10^4 \text{ cm}^2/(\text{Vs})$, $V_{ds} = 0$. (b) Dependence of the drain current on the drain voltage at different gate bias: (1) 0 V, (2) -0.1 V, (3) -0.3 V, (4) -0.4 V. $\mu_{QW2} = 700 \text{ cm}^2/(\text{Vs})$.

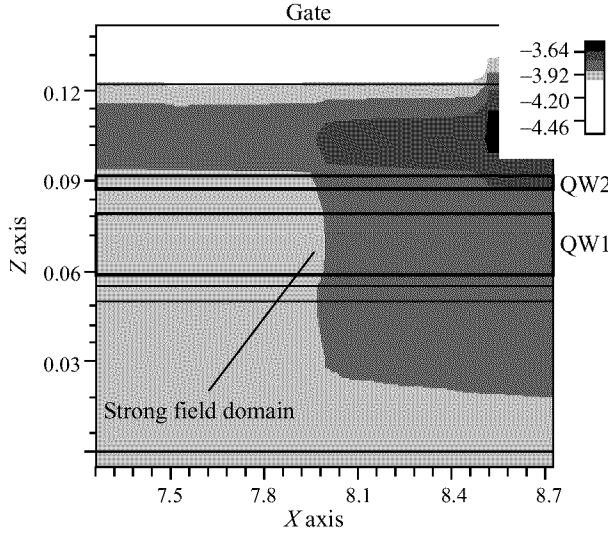


Fig. 3. 2D distribution of potential in the whole heterostructure. $V_{ds} = 0.56 \text{ V}$, $V_{gs} = 0$.

variation is realized not at minimum of μ_{QW2} . On the $I_{ds} - V_{ds}$ curves the negative differential resistance appears when drain-source voltage produces lateral electric field compared with transverse. The drain-source voltage drops stronger along the QW1 than the QW2 because the potential of QW2 is fixed by the gate. Therefore the energy levels gradient along the gate is different and the anticrossing takes place in some point under the gate at $V_{ds} = 0.52 \text{ V}$ that leads to strong decrease of mobility and charge accumulation near this point. The electric field is increased locally, the carrier velocity starts to saturate and results in further decreasing of mobility and charge accumulation. As a result, the strong field domain is formed under the gate (Fig. 3) and the lateral current is decreased. The condition of the domain formation is the sufficient decreasing of mobility at anticrossing. $I_{ds} - V_{ds}$ characteristics calculated for $\mu_{QW1} = 8000 \text{ cm}^2/(\text{Vs})$, do not possess the negative differential resistance region. In fact, this effect is the analog of the Gunn effect in bulk

semiconductor but in our case the effect is conditioned by interwell transfer of electrons. The calculation results don't differ practically for monotonic and nonmonotonic saturation velocity models (μ_{eff} is set as low field mobility in these models in TC QW, the nonmonotonic model describes the usual Gunn effect in GaAs). It indicates prevalence of interwell transfer over intervalley. The effect is stable to variation of the structure parameters so it is not numerical.

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